

# Magnetic moment manipulation by triplet Josephson current

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The induced magnetic moment, provided by the bands electrons, is calculated in a variety of Josephson junctions with multilayered ferromagnetic (F) weak link. The noncollinear magnetization of the F layers provides the conditions necessary to generate triplet superconducting correlations. It leads to the long-range induced magnetic moment, emerging in the superconducting (S) layers. It is shown to be dependent on the Josephson phase. By tuning the Josephson current, one may control the long-range induced magnetic moment. Alternatively, applying the voltage we can generate an oscillatory magnetic moment. The detection of such a spin effect may serve as independent evidence of the triplet superconductivity. The proposed mechanism seems to be attractive for superconducting spintronic devices with low dissipation.

The antagonistic nature of singlet superconductivity (S) and ferromagnetism (F) makes their coexistence in bulk systems rather difficult [1]. However a spatial separation of regions with the S and F order avoids natural limitation and was used in many experimental realizations of SF hybrid structures. The interplay of the superconducting and ferromagnetic long-range orders in hybrid structures via the proximity effect leads to a range of unusual physical phenomena [2–4]. For example, Josephson junction with a ferromagnetic interlayer may have a spontaneous phase difference  $\pi$  in the ground state. Such  $\pi$ -junction have been successfully implemented to strongly decrease the size of the single-flux-quantum circuits and reduce noise in a superconducting qubit [5].

Recently, a magnetic moment induced in the superconductor of a S/F bilayer was reported [6, 7] in accordance with the previous predictions [8–11]. Another unusual effect highlighted in the SF heterostructures is a triplet superconductivity. It was demonstrated theoretically [3, 12, 13] that a non-collinear magnetization in the SF heterostructures may lead to the creation of spin-triplet superconducting correlations with a non-zero total spin projection on the quantization axis. The exchange magnetic field does not destroy them, thus leading to a long-range superconducting correlations penetrating into the F region. The experimental evidence of such triplet correlations (TC) was revealed by the recent observation of long-range Josephson currents [14–16] that was an important breakthrough in this domain. Interestingly, though at the center of such Josephson junction the current is carried exclusively by the triplet component, it does not produce magnetic moment. Nevertheless the magnetic effect produced by the TC with the inherent nontrivial spin structure of the Cooper pairs also seems to be very attractive for applications. The challenging task

is to control the magnetic moment of the long-ranged TC to design new superconducting spintronics devices with low dissipation.

Here we demonstrate under which conditions it may be possible to generate the magnetic moment by the TC in the Josephson junction. Such induced magnetization occurs at a relatively large distance and it is sensitive to the superconducting phase difference. This opens interesting perspectives to couple the Josephson effect with spintronics.

For simplicity, we consider below the diffusive limit and a temperature close to the critical temperature  $T_c$  which allows to describe the underlying physics in the framework of the linearized Usadel equations. In this limit the F and S coherence lengths are  $\xi_f = \sqrt{D_f/h}$ ,  $\xi_s = \sqrt{D_s/2\pi T_c}$ , where  $D_{f,s}$  is the corresponding diffusion coefficient,  $h$  is the exchange field in the ferromagnet. To generate the long-range TC it is necessary to have non-collinear magnetization or spin-active interfaces. Here we concentrate on the case of a composite non-collinear F layer. We start with a SF'FS structure (Fig.1(a)) with semi-infinite S electrodes, and thicknesses  $d_L$  and  $d$  of the F' and F layers respectively. The origin of the  $x$ -axis, that is perpendicular to the layer plane, locates at the left SF' interface. The magnetization of the middle F layer is aligned along the  $z$ -axis, while the magnetization of the left F' layer is tilted by the angle  $\theta$  from the  $z$ -axis in the  $yz$ -plane (1). Naturally our results remain valid even if the magnetization of the F' layers are in the  $xz$ -plane. As it has been noted in [17], the optimal condition for the TC generation corresponds to  $d_L \lesssim \xi_f \ll d$ .

A SF heterostructure with a ferromagnet where an interface magnetization rotates easier than the magnetization in the bulk may serve as a suitable example. Note that it was found experimentally [18–20] that a thin layer of vanadium in the vicinity of an Fe interface shows different magnetization and coercitivity with respect to that in the main F layer. A suitable structure for the triplet

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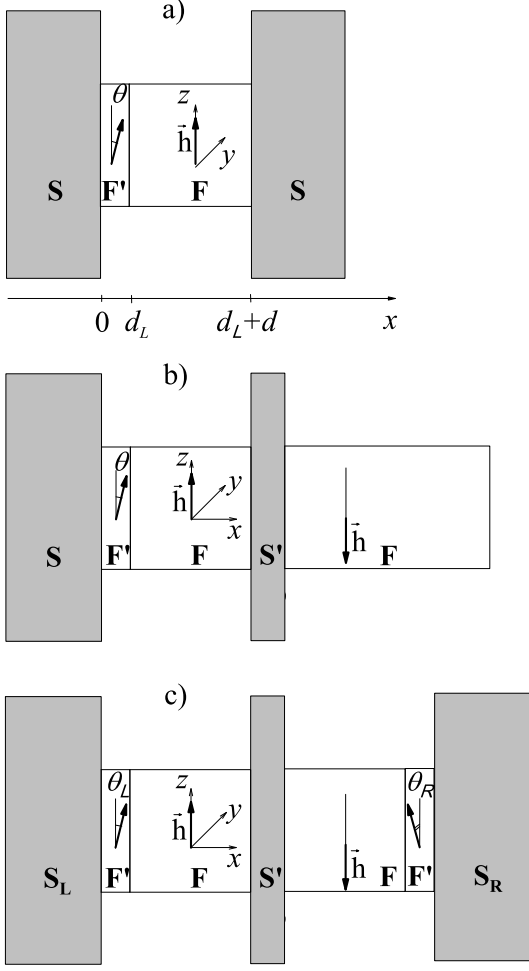


FIG. 1. The sketches of SF'FS Josephson junction (a), and more complicated structures (b) SF'F<sup>↑</sup>S'F<sup>↓</sup>, and (c) SF'F<sup>↑</sup>S'F<sup>↓</sup>F'S.

weak link may be also a combination of 3-d ferromagnetic films of different thicknesses or different compounds, having different anisotropy. It was shown [21] that the magnetic anisotropy of the Ni layer changes from the perpendicular to the in-plane with an increase of the layer thickness. Another example could be the Ni-CuNi combination, where the CuNi alloy exhibits a strong perpendicular anisotropy [22].

Near  $T_c$  the induced magnetic moment of the electrons (IMM) may be written as [23]

$$\delta \mathbf{M}(x) = -4\mu_B N_0 \pi T_c \sum_{\omega > 0} \text{Im} f_0(x, \omega) \mathbf{f}^*(x, \omega), \quad (1)$$

where  $N_0 = N_{0f}, N_{0s}$  is the density of states at the Fermi level in the F or S metal.  $f_0$  is a short-range singlet component, and  $\mathbf{f} = (f_x, f_t, f_z)$ , where  $f_x = 0$ ,  $f_z$  is short-range and  $f_t$  is long-range triplet component (TC) of the anomalous Usadel function. Consequently, only

the  $\delta M_y$  component of the induced magnetic moment may contain the long-range correlations.

The characteristic value of the IMM in the superconductor can be easily estimated from (1) to be of the order of  $\mu_B N_0 T_c$  [23]. It is by a factor  $T_c/h$  smaller than the electrons polarization in the ferromagnet.

The anomalous function obeys the linearized Usadel equations in the F and S metals [24]

$$\begin{aligned} \left(-D_{f,s} \frac{\partial^2}{\partial x^2} + 2\omega\right) f_0(x) + 2i\mathbf{f}(x) \cdot \mathbf{h}(x) &= 2\Delta \exp\left(\pm i\frac{\varphi}{2}\right), \\ \left(-D_{f,s} \frac{\partial^2}{\partial x^2} + 2\omega\right) \mathbf{f}_t(x) + 2if_0(x)\mathbf{h}(x) &= 0. \end{aligned} \quad (2)$$

The exchange magnetic field  $\mathbf{h}$  is present only in the ferromagnet, while the superconducting order parameter  $\Delta \neq 0$  only in the S layers,  $\varphi$  is the superconducting phase difference on the junction, the sign "+"(-)" is taken for the right (left) electrode. For  $d_L \lesssim \xi_f$ , we may use the Taylor expansion for the Usadel function  $f(x)$  in the thin left F' layer. In the F layer the function may be written in terms of its values at the interfaces [17]  $f_i(x) = f_i(d_L) \sinh q_i(d_L + d - x) / \sinh q_i(d) + f_i(d_L + d) \sinh q_i(x - d_L) / \sinh q_i(d)$ , where  $i = +, -, t$ , and  $f_{\pm}(x) = f_0(x) \pm f_z(x)$ ,  $q_t \equiv q_0 = \sqrt{2\omega/D_f}$ ,  $q_{\pm} = \sqrt{2(\omega \pm ih)/D_f} \approx (1 \pm i)/\xi_f$  at  $h \gg T_c$ . For simplicity, we assume the boundary resistance at the F'F interface is negligible and so we treat it as being zero, a thin normal metal interlayer influences insignificantly, the boundary resistance of SF interfaces is also zero, and so the anomalous Usadel function satisfy the boundary conditions [25]:

$$f(x)|_s = f(x)|_f, \quad \frac{\partial f}{\partial y}\bigg|_s = \gamma \frac{\partial f}{\partial y}\bigg|_f, \quad \gamma = \frac{\sigma_f}{\sigma_s}, \quad (3)$$

where  $\sigma_s, \sigma_f$  are the normal state conductivities of the S and F layers. The inequality  $\gamma \ll \frac{\xi_f}{\xi_s}$  provides so-called rigid boundary conditions, which allows to neglect the suppression of superconductivity in the S layer due to the proximity effect, thus  $\Delta = \text{const}$ . We may also use  $\Delta = \text{const}$  when the S electrodes are much wider in the  $y$  or  $z$  direction than the F link (Fig.1), if the F link is narrower than  $\xi_s$ .

The rigid boundary conditions yield:

$$\begin{aligned} f_0(d_L + d) &= \frac{\Delta}{\omega} \exp(i\varphi/2), \\ f_t(d_L + d) &= \gamma \frac{\xi_s}{\xi_0} f_t(d_L) / \sinh q_0 d, \\ f_t(d_L) &= -i \frac{d_L^2}{\xi_f^2} \sin(\theta) \frac{\Delta}{\omega} \exp(-i\frac{\varphi}{2}). \end{aligned} \quad (4)$$

This leads to suppression of the TC near the FS boundary due to the small parameter  $\gamma \frac{\xi_s}{\xi_0} = \frac{N_{0f}}{N_{0s}} \sqrt{\frac{D_f}{D_s}} \ll 1$ . Here  $\xi_0 = \sqrt{D_f/2\pi T_c}$  is the normal coherence length.

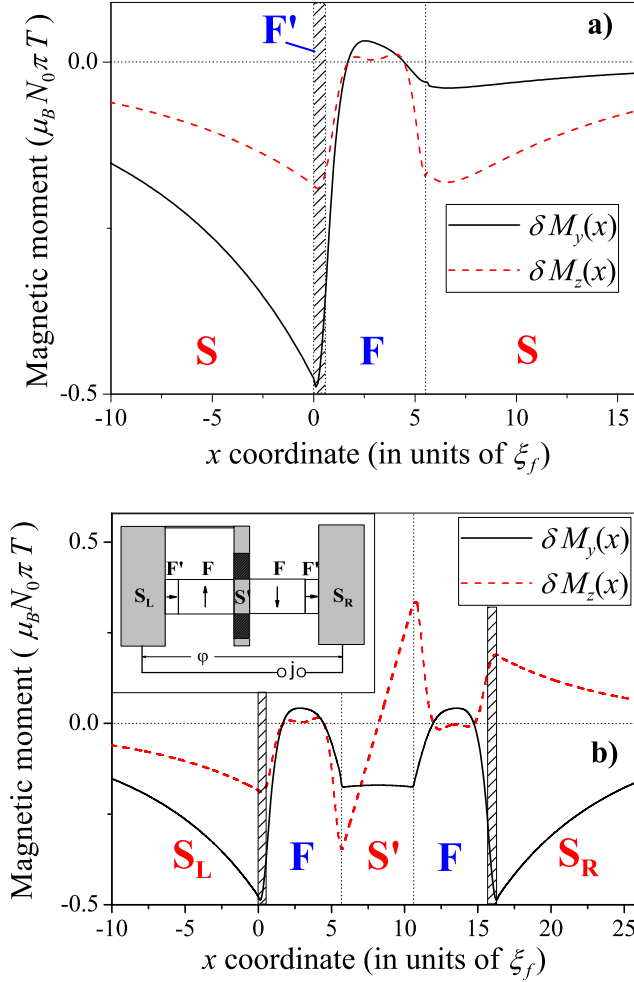


FIG. 2. (Color online) The induced magnetic moment distribution along (a) the SF'FS junction (Fig.1(a)), and (b) the structure in Fig.1(c). The inset shows the possible incorporation of the structure (Fig.1(c)) into a superconducting circuit.  $\xi_0 = 5\xi_f$ ,  $\xi_s = 10\xi_f$ , the thicknesses of layers  $d_L = d_R = 0.7\xi_f$ ,  $d = 5\xi_f$ , Josephson current is absent  $\varphi = \varphi_L = \varphi_R = 0$  and  $\text{Im}f_0 = 0$ .  $\theta = \theta_L = \theta_R = \pi/2$ ,  $T \approx 0.8T_c$ . The FS boundary parameter  $\gamma = 0.05$ .

Thus, we obtain the expression for the  $y$  component of the IMM in the right S layer

$$\delta M_y(x) = -4\mu_B N_0 s \pi T \frac{d_L^2 \sin \theta}{\xi_f^2} \gamma \frac{\xi_s}{\xi_0} \cos \varphi \times \sum_{\omega > 0} \frac{\Delta^2}{\omega^2} \frac{\exp[-q_s(x - d_L - d)]}{\sinh q_0 d}, \quad (5)$$

where  $q_s = \sqrt{2\omega/D_s}$ . If  $d \lesssim \xi_0$ ,  $d_L \sim \xi_f$ ,  $\gamma\xi_s/\xi_f \lesssim 1$ , the IMM (5) may be estimated at the FS boundary (at  $T \lesssim 0.5T_c$ ) as  $\delta M_y \sim -\mu_B N_0 s T_c \frac{\xi_f}{d} \sin \theta \cos \varphi$ .

At the center of the SF'FF'S structure, considered in the work [17], we have the triplet supercurrent but

the magnetization is zero because the singlet component vanishes. This component is necessary to generate the induced electron's magnetization (1).

The IMM has a maximum value near the FS interfaces. It decreases and oscillates at the distance  $\xi_f$  in the ferromagnet and falls down at the distance  $\xi_s$  in the superconductor in the considered SF'FS structure (Fig.2(a)).  $\xi_s$  is a characteristic scale of change of the anomalous Usadel function in a superconductor, therefore, the induced magnetic moment may be detected at a distance  $\lesssim \xi_s$  from the junction in the  $yz$  plane as well. The IMM (5) depends on the Josephson phase difference, because the triplet and the singlet components are generated by different S electrodes. The  $\delta M_y$  at  $\varphi = 0$  near the FS interface has opposite direction to  $M_y$  in the F' layer. It reminds the situation with the  $\delta M_z$ , that appears as a result of the short-range proximity effect near the FS interface and has a direction opposite to the F layer magnetization [8]. At the FS interface this component is phase independent and may be estimated as  $\delta M_z \sim -\mu_B N_0 s \pi \frac{\Delta^2}{2T} \gamma \frac{\xi_s}{\xi_f}$ , that corresponds to the short-range IMM calculated in the FSF sandwich [23].

The best way to isolate the phase sensitive  $\delta M_y$  component seems to be to consider the structure Fig.1(b) with the thin S' layer, sandwiched between two antiparallel ferromagnets. Due to the small thickness of the S' layer  $d_s \ll \xi_s$  the averaged induced  $\delta M_z$  component will be zero (Fig.2(b)). Calculating the triplet Usadel function at the S' layer we find

$$f_t(d_L + d) = -i \frac{d_L^2}{\xi_f^2} \sin(\theta) \frac{\Delta}{\omega} \exp(-i\varphi/2) \times \times \frac{\gamma\xi_s/\xi_0}{q_s d_s \sinh q_0 d + (\gamma\xi_s/\xi_0) \exp q_0 d}. \quad (6)$$

The amplitude  $f_t$  is maximal for  $d_s \rightarrow 0$ . However, the condition of the superconductivity existence in the S' layer imply  $d_s > \gamma\xi_s^2/\xi_f$  [2]. Nevertheless, this restriction may be easily overcome if the S' electrode exceeds the lateral dimension of F layers in the  $yz$  plane. In this situation the magnetic moment will be induced at the periphery of the S' layer where its inherent singlet superconductivity will coexist with the induced TC. The IMM in the S' layer (if  $d_s > \gamma\xi_s^2/\xi_f$ ) writes

$$\delta M_y(x) \sim -4\mu_B N_0 \pi T \cos \varphi \frac{d_L^2 \sin \theta}{\xi_f^2} \sum_{\omega > 0} \frac{\Delta^2}{\omega^2} \frac{\gamma\xi_s/\xi_0}{q_s d_s \sinh q_0 d}. \quad (7)$$

The Josephson junction corresponding to the setup (b) in Fig.1 should have extremely low critical current which complicates the in-situ phase control. The triplet Josephson junction presented in Fig.1(c) would have much larger critical current due to the interference between two sources of TC [17]. Let's consider the structure (Fig.1(c)) with the left and the right F' layers with magnetization aligned at the angles  $\theta_L$  and  $\theta_R$  to  $OZ$

axes, and thicknesses  $d_L$  and  $d_R$  respectively, the F layers have the same thickness  $d$ . If this structure is a part of the multiterminal device it is possible to have the different phases  $-\varphi_L$ , 0, and  $+\varphi_R$  respectively at the left, middle, and the right S electrodes. If the F layers have opposite magnetization and the parameters the F' layers are equal  $d_L = d_R$ ,  $\theta_L = \theta_R$ ,  $\varphi_L = \varphi_R$ , the  $\delta M_z$  component is antisymmetric relative to the center of the S' layer providing its zero average value, while the  $\delta M_y$  component is symmetric (Fig.2(b)), and may be written in the S' layer as

$$\delta M_y(x) = -4\mu_B N_0 \pi T \times \sum_{\omega > 0} \frac{\Delta^2}{\omega^2} \frac{\gamma \xi_s / \xi_0 [d_R^2 \sin \theta_R \cos \varphi_R + d_L^2 \sin \theta_L \cos \varphi_L]}{\xi_f^2 \sinh q_s d_s \sinh q_0 d}. \quad (8)$$

It contains the same attenuation parameter  $\gamma \xi_s / \xi_0$ . Note that the most suitable for the triplet magnetic moment generation should be the system with a very thin middle S' layer  $d_s \ll \gamma \xi_s^2 / \xi_0$ . In this case the attenuation of the TC vanishes but the superconductivity will be destroyed in the region between the F layers. However, if the lateral size of the S' layer exceeds that of the F layers, the singlet superconductivity will interfere with TC at the lateral distance  $\xi_s$  from the boundary of the F layer (shaded regions in Fig.2(inset)). In this region we have the optimal conditions for the IMM observation, for the structure (Fig.1(c)) at  $d_L = d_R \sim \xi_f$  and  $d \sim \xi_0$  the TC magnetization  $\delta M_y \sim -\mu_B N_0 T_c [\sin \theta_R \cos \varphi_R + \sin \theta_L \cos \varphi_L]$ . The exterior S electrodes may be considered as a source of the superconducting correlation, which forms the TC at the F'F boundaries, and penetrates at a long distance through the ferromagnet. Then the middle S' layer serves as a detector of the long-range induced magnetic moment (IMM). Let us consider for illustration the setup presented in the inset of Fig.2. Here the superconducting electrodes  $S_L$  and  $S'$  have the same superconducting phase but the superconducting current is flowing through the triplet Josephson junction  $S_L - S_R$ , the critical current of the  $S' - S_R$  junction being vanishingly small (because in this junction only a short ranged proximity effect is

possible). In such a case at the optimum conditions the IMM at the S' electrode should be  $\delta M_y \sim \mu_B N_0 T_c \cos \varphi$ , where  $\varphi$  is a phase difference on the junction.

Changing the applied Josephson phase or the Josephson current through the junction one may vary  $\delta M_y(\varphi)$  at fixed magnetization of the layers. In particular, applying the voltage to the Josephson junction, we create a situation, when the phase oscillates in time that results in the oscillations of the electron's magnetization, coupling the magnetic dynamics with the superconducting one. If some part of the S' electrode contains the magnetic atoms, the TC magnetization should polarize them. Assuming the typical value of the exchange interaction between electron's spin and the localized moment  $I \sim 10^3$  K and  $T_c \sim 10$  K, we may estimate that the TC polarization should be equivalent to the magnetic field  $\sim 1 - 10$  kOe.

Penetrating in other ferromagnet being in a contact with the S' layer, the IMM may operate its magnetization. The IMM tuned by the Josephson current may be used in spintronic devices instead of the spin-torque effect, which needs a significant dissipative current. Moreover, this effect may be used for operating the new types of the magnetic Josephson valve and memory [26], where the switch of the magnetization of a soft magnetic weak link changes the critical current of the readout Josephson junction.

In conclusion we have demonstrated that the superconducting triplet correlations can generate a magnetic moment, sensitive to the superconducting phase. In the Josephson junction with the composite non-collinear ferromagnetic interlayer this mechanism provides a direct coupling between the superconducting current and magnetization.

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